

Estimation of Flushing Time in a Monsoonal Estuary using Observational and Numerical Approaches

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Abstract

Estimation of flushing time (T_F) in an estuary is important for water quality analysis, and it is one of major transport time scales used in estuaries to quantify the hydrodynamic processes and for water resources management strategies. Thus, the main objective of the present study was to estimate the T_F in the Mandovi estuary (a monsoonal estuary) on the west coast of India. In the study, field observations of salinity (FOS), and a numerical model are used to describe the T_F during the southwest monsoon (heavy river discharge), post-monsoon (moderate river discharge) and pre-monsoon (negligible river discharge). T_F was calculated for 12 (months) river discharge scenarios (the calculation was done under monthly mean flow conditions). Among the 12 scenarios, four scenarios were within an extremely low flow range: $0.8 \text{ m}^3\text{s}^{-1}$ – $2.2 \text{ m}^3\text{s}^{-1}$; four were in a moderate flow range: $4.3 \text{ m}^3\text{s}^{-1}$ – $67 \text{ m}^3\text{s}^{-1}$; and the remaining four were in a high flow range: $119.0 \text{ m}^3\text{s}^{-1}$ – $506.6 \text{ m}^3\text{s}^{-1}$. The T_F calculated from FOS and numerical model showed good matches during the periods of heavy river discharge and moderate river discharge. Results from FOS (numerical model) showed that the T_F was 1.12 (1.11) days for a river flow of $506.6 \text{ m}^3\text{s}^{-1}$ (during the southwest monsoon), and the T_F reached 251.28 (592.38) days under extreme low flow of $0.8 \text{ m}^3\text{s}^{-1}$ (during the pre-monsoon). Regression equations fitted by power and exponential functions were derived from FOS and numerical model simulations to correlate T_F with monthly mean river discharges. The power regression equation derived from FOS (numerical model) showed good statistical fit with data ($r=-0.997$ (-1.0)) for any given river discharge compared to the exponential regression equation ($r=-0.81$ (-0.80)). Hence, the power regression equation can be used for the rapid evaluation of the impact of drought (during the pre-monsoon) and flood (during the sw-monsoon) scenarios in the estuary.

Keywords: salinity; tides; flushing time; numerical modelling; freshwater discharge; the west coast of India.

1 Introduction

Understanding the hydrodynamics and transport time scales are the key factors for good management of estuaries. Water resources management strategies to maintain adequate freshwater inflows are critical in order to avoid long residence times and water quality problems in estuarine ecosystems (Huang et al. 2011). There are several transport time scales to quantify the rate of renewal of water in an estuary. Fundamentally, four transport time scales are used, they are (i) T_F , (ii) age, (iii) residence time, and (iv) exposure time. T_F is the time required to replace the existing freshwater in an estuary at a rate equal to the river discharge (Pritchard 1960; Officer 1976; Knauss 1978; Thomann and Muller 1987; Dyer 1973, 2000; Bowden 1967; Fischer et al. 1979). Residence time is the time required for a parcel of water to escape the estuary from an existing location (Dronkers and Zimmerman 1982; Sheldon and Alber 2002; Orfila et al. 2005; Gourgue et al. 2007; Huang et al. 2011). Another transport time scale, age is the time required for a water parcel to move from a defined inlet to its present location (Zimmerman 1988; Monsen et al. 2002). Some water parcels that leave an estuary during the ebb tide come back to the estuary at later time, possibly during the flood tide. This fact is accounted in the concept of exposure time, which is defined as the total time spent in the domain of interest until the parcel never return to the estuary (Monsen et al. 2002; Delhez 2006; Wolanski 2007). In the present study, we apply the T_F concept in a monsoonal estuary on the west coast of India using freshwater fraction method (hereafter FWF method).

The estuaries, of the Indian peninsula, are called monsoonal estuaries and the Mandovi estuary on the west coast of India is one of these estuaries. The monsoonal estuaries receive heavy river discharge during the southwest monsoon (June–September) here after termed as sw-monsoon. Two parameters based on river discharge, which distinguish a monsoonal estuary from other estuaries are, (i) the ratio of volume of total annual river discharge to volume of the estuary and (ii) the ratio of maximum monthly river discharge to mean monthly river discharge (Vijith et al. 2009). The monsoon rainfall and associated freshwater inflow into these estuaries play an important role on tides, salinity distribution, sediment transport and ecosystem. The freshwater inflow provides necessary nutrients and maintains appropriate flushing to assure the biological productivity of the system (Huang and Spaulding 2002).

The Mandovi resembles the physical characteristics of other estuaries along the west coast of India hence it was chosen for the present study. The length of the Mandovi is 50 km and average depth is five meters. The width varies from 3.7 km at the ocean point to 0.1 km at the upstream end of the estuary, and the catchment area is 1895 km². The average estuarine volume is 102.09 Mm³. A narrow

canal, called the Cumbarjua Canal, from the Zuari estuary and several other tributaries also join the Mandovi (Figure 1). This estuary discharges into the Arabian Sea at the ocean point, and at the upstream end, the main source of freshwater input is from the Mhadei river that originate in the Western Ghats. A hydrological model result shows that the annual river discharge into the Arabian Sea from the Mandovi is about 6004 Mm^3 (Suprit and Shankar 2008). Tides in the Mandovi are of the mixed semi-diurnal type and the tidal ranges are about 2.3 and 1.5 m during the spring and neap tides, respectively (Manoj et al. 2009).

In this paper, our objective was to calculate the T_F in the Mandovi using the field observations of salinity (hereafter FOS) and using a numerical model. In addition, regression equations by power and exponential functions have been derived from FOS and numerical model simulations to correlate estuarine T_F for varying river discharges. FOS, numerical model are used to describe the T_F during the heavy river discharge ($119\text{--}506 \text{ m}^3\text{s}^{-1}$), moderate river discharge ($4.3 - 67 \text{ m}^3\text{s}^{-1}$) and negligible river discharge ($0.8\text{--}2.2 \text{ m}^3\text{s}^{-1}$). Alber and Sheldon (1999) found the considerable intra-seasonal and inter-annual variability in T_F in five riverine estuaries in Georgia, U.S.A. The intra-seasonal and inter-annual variability in T_F prompted them to evaluate T_F for a range of flow conditions rather than ascribing one T_F to a system. In the present study, we estimated the T_F for each month in accordance with the prevailing monthly mean flow conditions.

2 Material and Methods

2.1 Salinity Data

The *in situ* measurements of salinity were carried out using CTD (SBE 19plus) during June 2007–May 2008 in the Mandovi. The observations, along the longitudinal sections of the estuary, were carried out twice in a month to get an average salinity structure over the vertical column, and to find the changes in salinity from the ocean point to the upstream regions in each month.

The stations where FOS were carried out are shown in Figure 1. There are total 17 stations in the estuary where observations were carried out. Please note that during the sw-monsoon, the observations were limited up to the station, M8 as the remaining upstream stations are fully freshwater during this period. The observations were extended further upstream stations according to the monsoon withdrawal from this region. The entire stations were covered during the pre-monsoon. Similarly the observations were not conducted at the ocean point of the estuary (3.7 km away from the first station (M1)) in June 2007–May 2008 due to the following facts (i) as the research vessel cannot sail through the area due to the formation of sand bar during the sw-monsoon, (ii) and the rest

of the seasons, our previous observations show that there is no change in salinity from the ocean point to M1 due to strong tidal mixing.

The *in situ* measurements of salinity obtained thus was averaged vertically in each station. After that, the vertically averaged data were interpolated from ocean point to upstream end point (see Ganjem in Figure 1) of the estuary. The total length of the Mandovi is 50 km from the ocean point to Ganjem and, this length was divided into five segments equally. Subsequently, the FWF was calculated in each segment of the estuary.

2.2 River Discharge & Estuarine Volume Data

The monthly mean average discharge data available at Ganjem (head of the Mandovi) during 1979–2000 were used as the freshwater input. The freshwater inputs from the local effects such as evaporation, precipitation, etc. was not considered in this study. The river discharge data were obtained from Central Water Commission, Government of India.

2.3 Details of the Numerical Model

In addition to relying on FOS for the estimation of T_F , it is also desirable to check the reliability of these estimates with a numerical model. For this purpose, a hybrid network numerical model (Manoj and Unnikrishnan 2009) is used in this study. The hybrid network numerical model (hereafter H2N-Model) is a two-dimensional model (2D) coupled to one-dimensional model (1D). The 2D model was used in the downstream (wide) regions of the estuary, and the 1D model was used in the narrow upstream regions. A Cartesian Coordinate Grid was used in the H2N-Model and the grid resolution was chosen as 500 m both in x and y-axes. The differential equations governing the tidal circulation and salinity distribution, in the H2N-Model, are equations of momentum, continuity and advection-diffusion equation for salinity. The equations were solved using the finite difference explicit method on an Arakawa C grid and the leapfrog technique to march in time.

The model was calibrated and verified using the time series measurements of salinity conducted in the Mandovi during April (pre-monsoon) and August (sw-monsoon period), 1993. For the simulation of salinity, the model was initialized with constant salinity at different sections of the model domain based on the observations. There is no continuous measurements of salinity in the Mandovi to force the model at the open boundary (except three day data each in April and August 1993). However, the model can be forced at the mouth with a constant salinity value. The salinity at the mouth of the Mandovi remains as a constant value throughout the tidal cycles from October to May (see Figure 2),

hence salinity can be defined as a constant value at open boundary. For the simulations of salinity, the model was forced at the mouth using a constant salinity value prevailed in April, and salinity was defined as a cosine function in August. The model was run for 41 days and the 38th–40th day’s simulations at three locations, namely, at mouth, middle and upstream regions in the Mandovi during the model verification period are shown in Figure 3. The upper panel (A) shows the salinity on 19–21 August 1993 and lower panel (B) shows the salinity on 07–09 April 1993. The simulations are in reasonably good agreement with the observations. The upper panel (A) of Figure 3 shows that the estuary is fully freshwater in the middle and upstream regions in August (the details of model boundary conditions for computing T_F are described in section 3.2 of Results).

2.4 Calculation of T_F by FWF method

The FWF method is a steady state calculation that can be readily applied, as it only requires information about freshwater volume and river discharge, and in this method, the freshwater volume is calculated from the measurements of salinity at different sections in an estuary (Officer 1976; Alber and Sheldon 1999; Huang and Spaulding 2002; Huang 2007).

Assuming a linear mixing process in the estuary, the FWF can be written as follows:

$$fr = \frac{S_0 - S_l}{S_0} \quad (1)$$

Freshwater volume of particular section or an entire estuary can be written as

$$f_{avg} = \int fr \, dv \quad (2)$$

The equation of T_F can be written as follows:

$$T_F = \frac{f_{avg} V}{Qr} \quad (3)$$

where the symbols are:

- fr = Freshwater fraction
- f_{avg} = Freshwater Volume of particular section
- S_0 = Normal ocean salinity
- S_l = Salinity at given location inside the estuary
- Qr = Monthly mean averaged discharge
- V = The volume the entire estuary
- T_F = Flushing Time

3 Results

3.1 Salinity Distribution

Large changes in the salinity distribution occur from the ocean point to the upstream regions in the Mandovi annually. The heavy rainfall and associated river discharge during the sw-monsoon limit the salinity distribution to the first 12 km from the ocean point of the estuary, and this stretch is fully stratified during the above period. The remaining upstream regions become fully freshwater. Figure 2 shows the vertically averaged salinity from the ocean point to the upstream regions. As seen in Figure 2 (a–d), the large variations in salinity observed from the ocean point to the upstream regions were due to the heavy river discharge during the sw-monsoon.

A numerical model study in the Mandovi by Unnikrishnan et al. (1997) showed a downstream velocity of 1.5 ms^{-1} for a river discharge of $100 \text{ m}^3\text{s}^{-1}$ at the upstream regions of estuary. The tidally averaged currents (over a M_2 tidal cycle) were about 20 cms^{-1} for a river discharge of $400 \text{ m}^3\text{s}^{-1}$ at the ocean point (Manoj 2008). These results indicate that the downstream velocity associated with heavy river discharge can flush out salinity several times from the head to the ocean point during the sw-monsoon. As seen in Figure 2 (a–d), the large changes in the salinity distribution were observed from the ocean point to the upstream regions between 1st June and 27th June 2007; between 10th August and 24th August 2007 (see Figure 2 (a– c)). Decreases in salinity in the estuary due to the sw-monsoon stop by the end of September and salinity level start increasing after sw-monsoon. Figure 2 (e–h) shows that salinity intrudes into further upstream regions by October onwards. The estuary becomes partially mixed during the October – December period from the stratified conditions prevailed during the June–September.

Salinity showed in Figure 2 (g) is the measurement at the surface of the water column. Salinity data over the depth were lost due to the malfunctioning of CTD on the sampling day (14 December 2007). As the estuary is very shallow, salinity does not change much from the surface to bottom during the post-monsoon and pre-monsoon seasons. The Figure 2 (g) also shows the intrusion of salinity toward the upstream regions. Figure 2 (i–l) shows the salinity distribution during the pre-monsoon. The estuary is well mixed during this period and salinity is about 35 *psu* at the ocean point, and gradually reduces to zero at the upstream end. The changes in salinity found during the sw-monsoon and post-monsoon seasons are completely vanished during this periods due to the strong tidal mixing. The tidal currents in the estuary become strong in the absence of river discharge. The tidal currents ($0.8\text{--}1.0 \text{ ms}^{-1}$) found in the estuary are sufficient to keep the water column vertically well-mixed in the absence of the river discharge (Manoj and Unnikrishnan 2009).

3.2 T_F from FOS and H2N-Model

For computing the FWF from the observations of salinity, the observed values of salinity for each section were applied in Equation 1. For computing the FWF from the H2N-Model, the model was run with the inputs of salinity and tides at the open boundary. For simulation of salinity in each month, a constant value of salinity prevailed in that particular month was used to force the model at the open boundary, and the freshwater input prevailed in each month at the upstream end of the estuarine boundary (Table 1). The model was run for 41 days. The salinity values obtained from the model were applied in Equation 1 and FWF for each section were calculated. After that, the freshwater volume of each section was calculated using the Equation 2. The T_F for the entire estuary was calculated using the Equation 3.

The T_F calculated from FOS and H2N-Model are shown in Figure 4, and the results are also summarised in Tables 2–4. T_F shows large intra seasonal variations during the sw-monsoon. (Figure 4 (a)), post-monsoon (Figure 4 (b)), and pre-monsoon (Figure 4 (c)). T_F found from the observations (model) during the sw-monsoon are about 1–3 (1–4) days. Both the observation and model results show that T_F is lowest during July and August and becomes highest in the month of April. In this region, under normal conditions, the onset of sw-monsoon is in the 2nd week of June and the withdrawal of sw-monsoon is by the end of September, interestingly the T_F is about seven days during the onset and withdrawal months (Table 2). This is because of the freshwater inputs to the Mandovi during the above two months are almost the same (Table 1).

The T_F in the months of July and August 2007 show a very good comparison between the observation and model. Also, there are reasonably good matches from September to December. The T_F from model shows a consistent increase in T_F after September 2007, and the T_F doubles from January to April 2008 in comparison to the observation, while the observation also shows an increasing trend in T_F after September, there is no consistent increasing trend. For example, the T_F is decreased on 16th November 2007 and 22nd February 2008, the results also show that T_F is dropped from 227 days on 18th April to 199 days on 2nd May 2008. The highest value of T_F found from the observation (model) is 251 (592) days on 4th of April 2008.

3.3 Regression Equations to Correlate T_F with River Discharges

The T_F calculated from FOS and H2N-Model show that the T_F decreases sharply as the river

discharges increase. The T_F varies from estuary to estuary due to the variation in freshwater volume and river discharge. So it is important to establish a functional relationship between estuarine T_F and river discharge (Asselin and Spaulding 1993; Cifuentes et al. 1990; Alber and Sheldon 1999). Once this relationship is established, it can provide a quick approach for water resource engineers and managers to calculate the estuarine T_F in response to the changes of freshwater input (Huang and Spaulding 2002). Once a good regression equation is derived, it can be used as a base to evaluate whether further investigations are needed for more details and more expensive 3D numerical models simulations (Huang et al. 2011). To establish the relationship between river discharge and T_F in the Mandovi, we used two regression models, namely, power and exponential regression equations.

The equation for power regression can be expressed as follows:

$$T_p = AD^B \quad (4)$$

The equation for exponential regression can be expressed as follows:

$$T_e = AB^D \quad (5)$$

where T_p and T_e are T_F by power exponential functions respectively; D is the discharge variable; A and B are regression coefficients.

The power and exponential regression relationships between T_F and river discharges were established using Equation 4 and Equation 5 respectively. T_F from FOS and H2N-Model was analysed separately and the results are shown in Figures 5 – 6. Power regression showed a negative correlation of 0.99 for the relationship between T_F and river discharge calculated from FOS (Figure 5 (a)), and a perfect negative correlation was obtained for the relationship between T_F and river discharge calculated from H2N-Model (Figure 5 (b)). In the case of exponential regression, a negative correlation of -0.81 (-0.80) from FOS (model) was obtained (Figure 6 (a-b)).

4 Discussion

Our primary interest of this study was to calculate the T_F in the Mandovi during three different seasons in a year. For this purpose, we adopted two approaches, first the computation of T_F from FOS. The application of H2N-Model was another approach to calculate the T_F in the estuary. The FWF method was used to calculate T_F in the Mandovi as it is one of the cost effective methods for calculating T_F in an estuary. Even though the steady state of salinity is an underlying assumption of FWF method, and it is generally known that monsoonal estuaries never attains steady state, the Mandovi is a spacial case. The observations show that the major part of the monsoonal activities in

the estuary are restricted to June-September and the estuary remains in the steady state in the remaining seven to eight months. The estuary also receives a considerable amount of freshwater discharges up to January. So employing FWF method is justified to get a firsthand information of T_F in this kind of estuaries.

Though the H2N-Model is vertically averaged model that cannot capture the vertical circulation precisely, as we stated above, the major part of the monsoonal activities in the estuary are restricted to June-September and the estuary becomes partially-mixed to well-mixed conditions in the remaining seven to eight months. This fact has encouraged us to use H2N-Model to compute T_F in the Mandovi. The important thing to note that the purpose of using a numerical model was not to simulate the T_F obtained from FOS as it is not possible to simulate the T_F accurately for *in situ* measurements of salinity. Even so, the results from the above two approaches are put together for a comparison. The model results showed reasonably good comparison during the sw-monsoon and post-monsoon seasons. But the model overestimated T_F during the pre-monsoon.

The FOS show that intra-seasonal changes occur in the salinity distribution in the Mandovi. Break in rainfall occur many times during the sw-monsoon in this region (Ramanadhan et al. 1973; Vecchi and Harrison 2002; Rameshkumar and Dessai 2004). The breaks in rainfall during the sw-monsoon leads to intra-seasonal changes in salinity in the estuary. During the sw-monsoon, from the previous studies, the normal salinity range is 7–22 *psu* at the ocean point.

Figure 2 (c) shows that the salinity is 5 *psu* on 10th August 2007 i.e., below the normal low value (7 *psu*) at the ocean point whereas the salinity is about 30 *psu* on 24th August 2007. This increase in salinity on 24 August 2007 was due to the break in the sw-monsoon. Salinity is decreased to 12 *psu* after two weeks (7th September 2007) when the sw-monsoon once again got intensified due to heavy rainfall (the rainfall data analysed for the above months are not shown here). Salinity increases in the Mandovi by the end of September as the sw-monsoon withdraws from this region (see salinity profile shown for 21 September in Figure 2(d)). After sw-monsoon, the salinity difference found at the ocean point disappears and salinity remains above 30 *psu* from October to May. The changes in the salinity distribution during the breaks in the sw-monsoon affect the freshwater volume of the estuary and finally the T_F .

T_F in April from observation (model) is about 251(592) days for a river discharge of $0.8 \text{ m}^3\text{s}^{-1}$ and in May, T_F is 192 (525) days for a river discharge of $0.9 \text{ m}^3\text{s}^{-1}$. These results indicate that T_F is very

sensitive to small river discharges. The results obtained from both FOS and H2N-Model indicate that the T_F is relatively stable for the higher values of river discharge, but as the river discharge goes down, the T_F increases sharply as seen in Figures 5 – 6. Since the power regression equations show an excellent correlation between T_F and river discharge for any given discharge value, compare to exponential regression equations, the power regression equations can be used for the rapid evaluation of the impact of drought (during the pre-monsoon) and flood (during the sw-monsoon) scenarios in the Mandovi. However, it is important to note that a regression equation may produce large error in comparison to a numerical prediction when the river discharge reduces to minimum inflow conditions (Huang et al. 2011).

4.1 Impact of Low T_F on the Estuarine Ecosystem

The Mandovi is one of the less polluted estuarine systems on the west coast of India due to the monsoon, and less industrial activities along the banks of this estuary. The monsoon plays an important role on the biogeochemistry of this estuary. There are some industrial and mining activities that discharge nutrients and heavy metals into the estuary (Nigam et al. 2005; Alagarsamy 2006; Kessarkar et al. 2010). A study by Maya et. al. (2009) shows that the concentrations of NO_3 , NO_2 , NH_4 , PO_4 and SiO_4 are 10.82, 0.78, 4.19, 1.0, 82.10 (0.11, 0.59, 0.00, 0.23, 8.11) respectively during the sw-monsoon (post-monsoon) in the Mandovi. Dissolved oxygen, Dissolved organic carbon (DOC), Dissolved organic nitrogen (DON), Chlorophyll, etc. are also found in very high concentration during the sw-monsoon compared to the post-monsoon. Another study by Khodse et al. (2010) shows that the transport of total dissolved carbohydrate rich (11 to 60%), dissolved organic matter from the Mandovi to the coastal waters during the monsoon season may affect ecosystem function by fuelling biological activity of heterotrophic micro-organisms. Excess nutrients, physical pollutants, etc. in the water column affect the living species, water quality and finally damage the ecosystem in the absence of sufficient river inflow. Our study shows that the low T_F found during the sw-monsoon and post-monsoon seasons can keep the ecosystem of the Mandovi free from the polluting substances up to a good extent.

As we know, the ecosystem of an estuary comes under serious threat when an estuary experiences the deficit of freshwater inflow either due to the deficit in rainfall or plans such as the diversion of water into other basins from the upstream regions of the estuary. The diversion of freshwater inflow from the upstream region may change the transport of sediments into an estuary and coast, and this may lead to erosion of banks and shoals. The two-layer circulation of water within the estuary may be weakened and reduce the inflows of offshore bottom water in absence of sufficient freshwater

inflow (Olsen et al. 2006). The low river input to an estuary leads to a high T_F , which in turn accumulate the pollutants in an estuary and destroy the ecosystem, and lead to serious freshwater shortage for drinking and farming activities. The Mandovi is one of the estuaries, in this region, comes under this threat due to the plan to divert water into the other basins. Our study shows that the T_F is very high during the pre-monsoon in the Mandovi so the utmost care is needed while carrying out such plans in estuaries like that of the Mandovi.

5 Conclusions

The T_F in the Mandovi was determined by the FOS and H2N-Model. This study showed seasonal changes in T_F during the sw-monsoon, post-monsoon and pre-monsoon seasons. Both observations and numerical model showed consistent results during the periods of heavy and moderate river discharge. The estuaries along the west coast of India are heavily depended on the sw-monsoon for river input. Our present study in the Mandovi shows that the low river discharge into the estuaries along this region can increase T_F significantly, which is vulnerable to the healthy ecosystems of these regions. Run-off reaches to about $\sim 1 \text{ m}^3\text{s}^{-1}$ from March to May in the estuary. The flushing decreases after January in the estuary until the onset of next monsoon (in June) and this can lead the estuary to be flushed with seawater few times during the long dry periods as the mean tidal range in this estuary is about 2m. So the other methods such as tidal prism method can be employed to get more accurate results of T_F during the above period. But this is out of the scope of this paper. The T_F values from H2N-Model are twice that of observation during the pre-monsoon. This indicate that model needs further calibration during this period. However, in essence, our results indicate that the H2N-Model can be used for the Mandovi to examine various freshwater withdrawal scenarios. The power regression equations derived from FOS and H2N-Model simulations showed good statistical fit with data. These equations can be used for rapid evaluation of the impact of drought and flood scenarios in the estuary.

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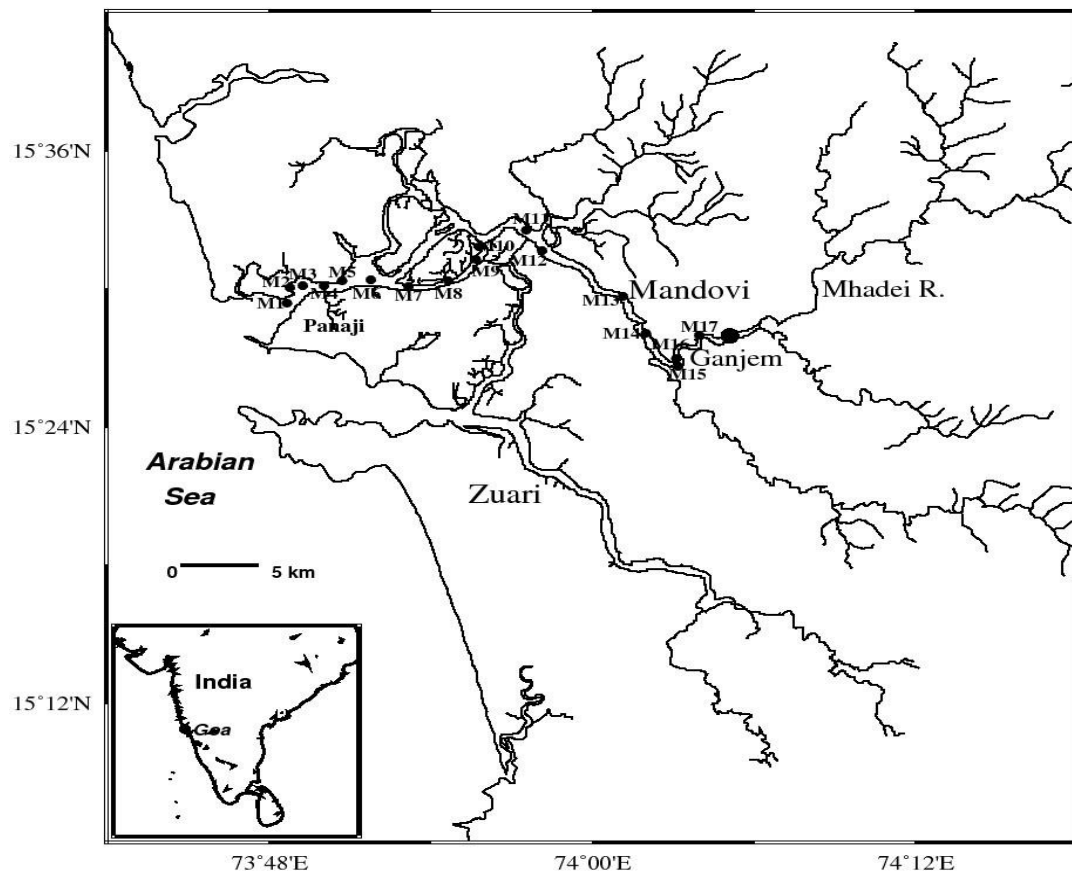


Fig. 1.

Figure 1. Map shows the Mandovi estuary on the west coast of India

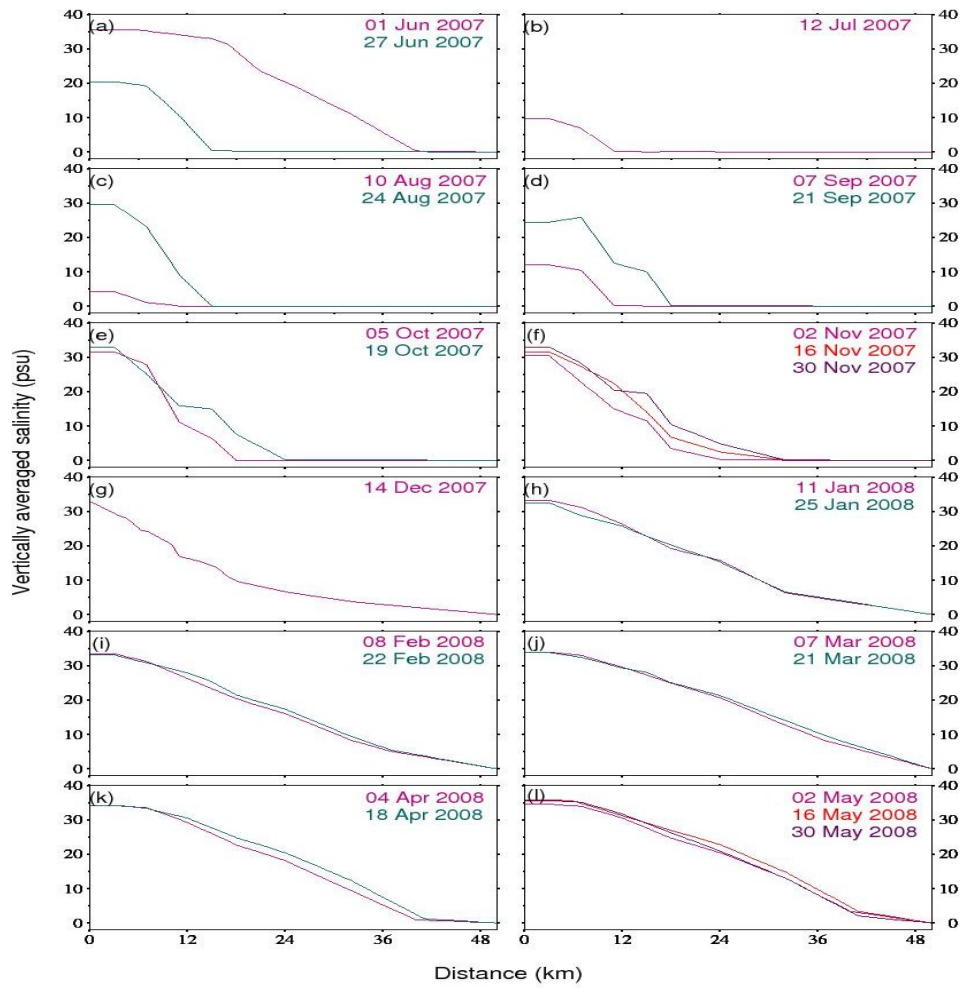


Fig. 2.

Figure 2. Vertically averaged salinity in the Mandovi estuary. The observations of salinity were carried out during the period of June 2007–May 2008. The date, month and year of observations of salinity are shown on the right top of each panel. Salinity showed in the panel (g) is the measurement at the surface of the water column.

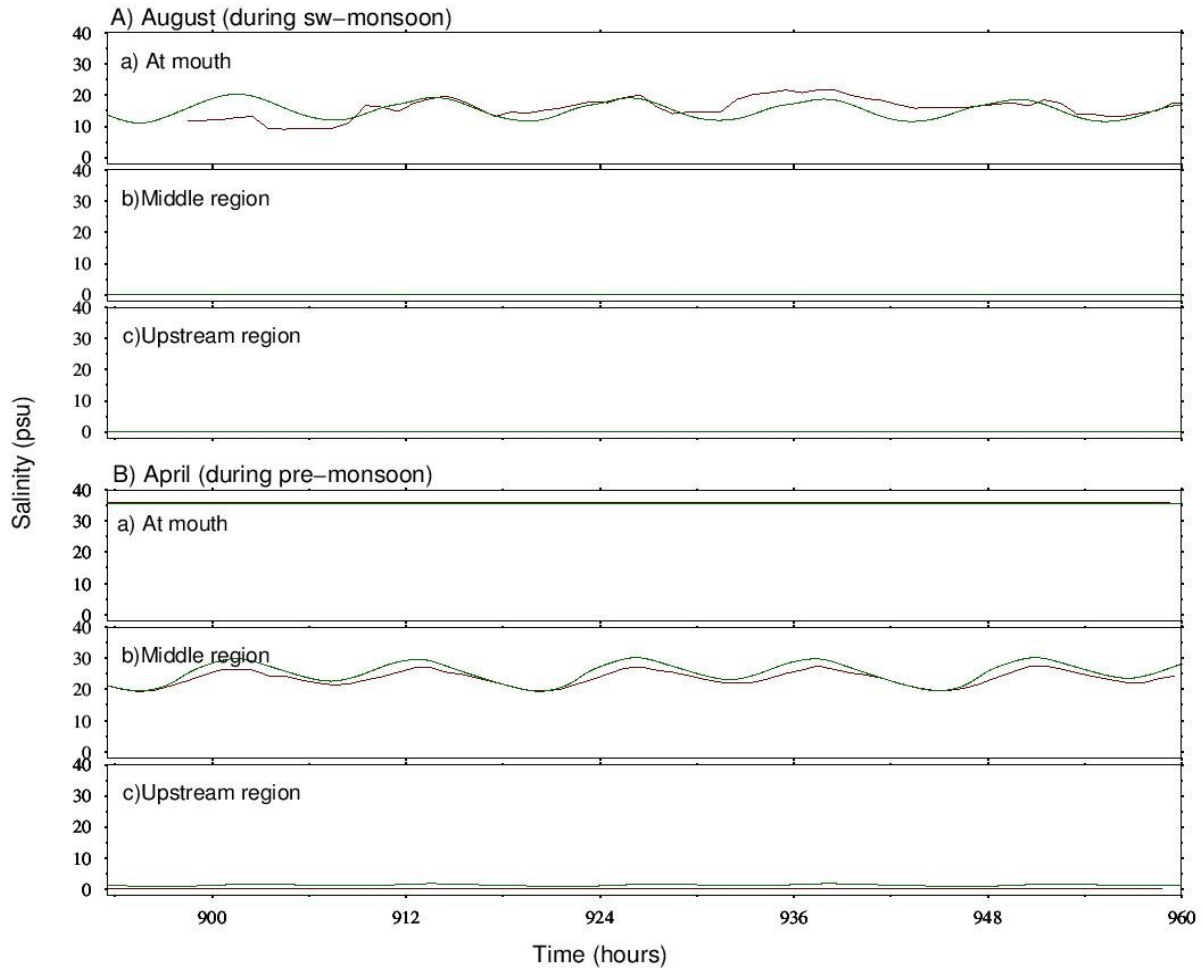


Fig. 3.

Figure 3. Observed (red) and simulated (green) salinities at the mouth, middle and upstream regions in the Mandovi during the model verification periods in April (during pre-monsoon) and August (sw-monsoon) in 1993. 898.5 hours on X axis of the upper panel (A) correspond to 0.0 hours 19/08/1993; 893.5 hours on X axis of lower panel (B) correspond to 00.0 hours on 07/04/1993.

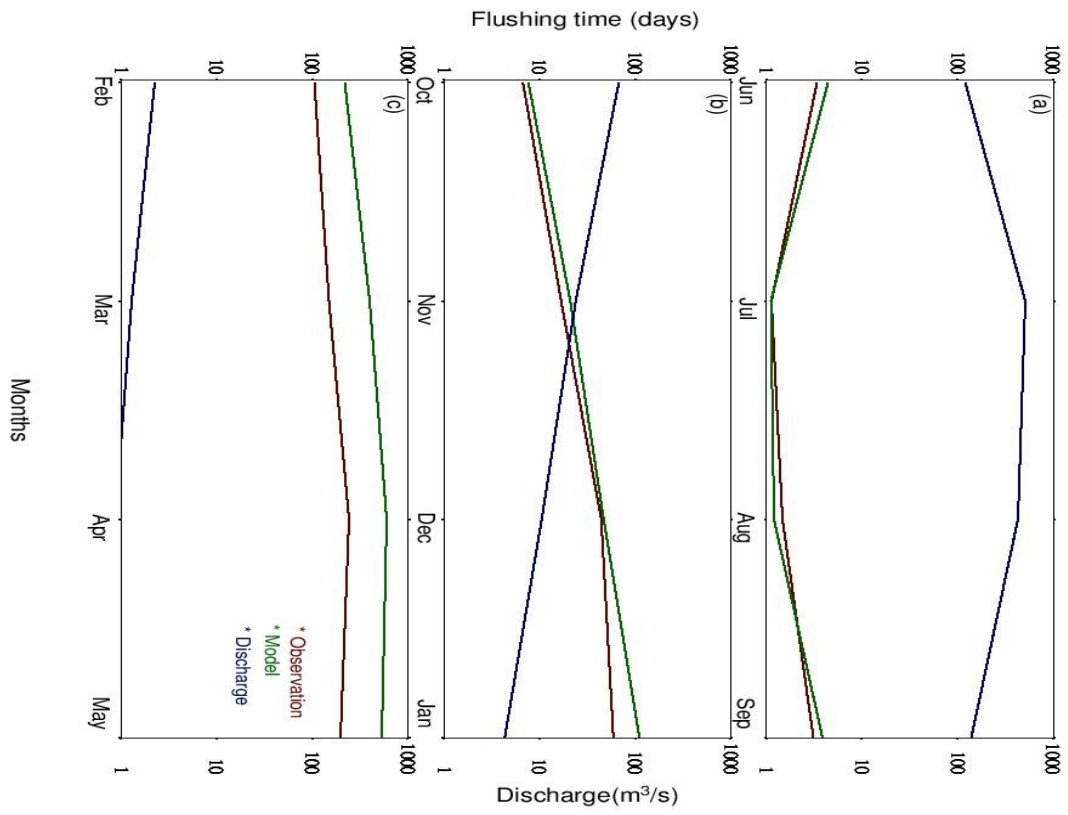


Fig. 4.

Figure 4. Semi-log plot of T_F and monthly mean averaged river discharge in the Mandovi estuary. The T_F showed in panels (a), (b), and (c) are respectively for sw-monsoon, post-monsoon, and pre-monsoon seasons

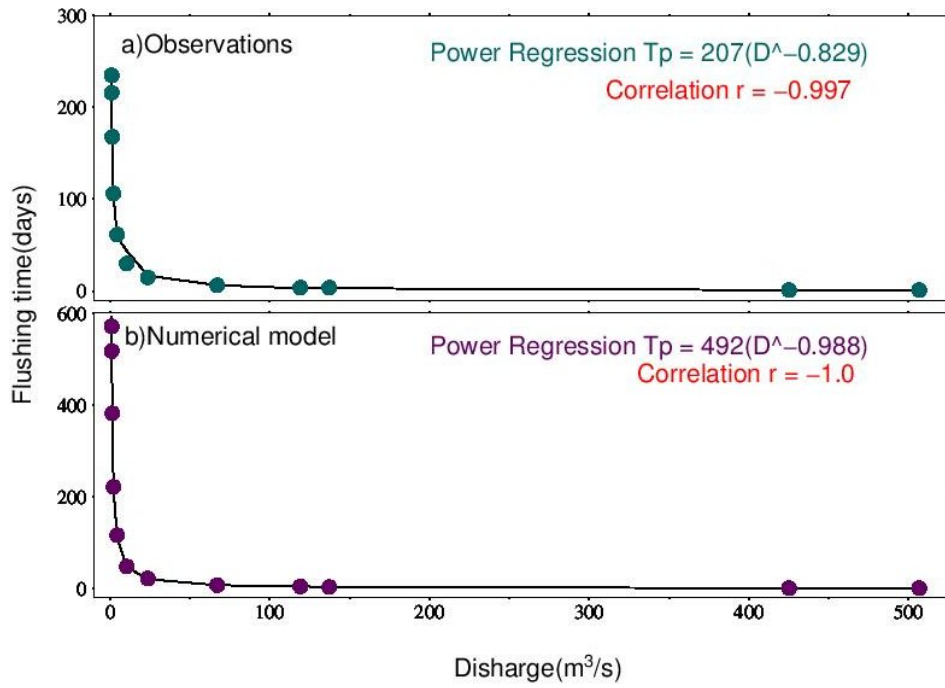


Fig. 5.

Figure 5. Regression fit by a power function between FOS (model) of T_F and river discharge

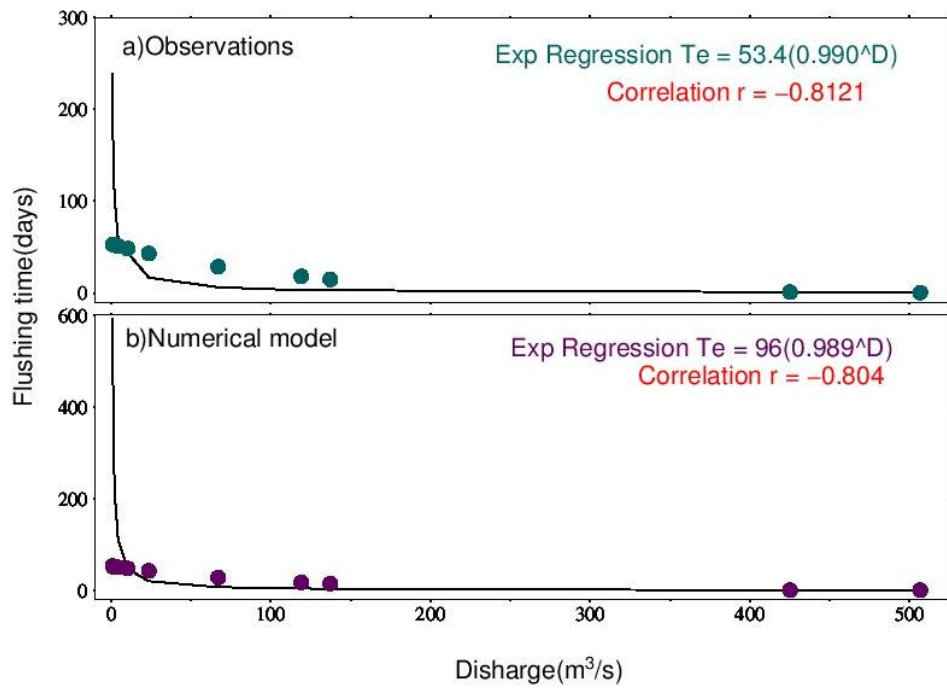


Fig. 6.

Figure 6. Regression fit by an exponential function between FOS (model) of T_F and river discharge

Table. 1. Monthly mean averaged discharge at Ganjem in the Mandovi

Months	Monthly Mean Averaged Discharge (m^3s^{-1})
June	119.00
July	506.60
August	425.30
September	137.30
October	067.00
November	023.70
December	010.40
January	004.30
February	002.20
March	001.20
April	000.80
May	000.90

Table. 2. Flushing time during the sw-monsoon

		Segment-1		Segment-2		Segment-3		Segment-4		Segment-5	
Segment Vol. (10^6 m^3)		89.58		14.40		9.23		6.84		2.78	
		Obs	Model	Obs	Model	Obs	Model	Obs	Model	Obs	Model
01 June 2007	F _{FW}	0.004	0.18	0.09	0.69	0.44	0.90	0.78	0.99	0.99	1.00
	V _{FW} (10^6 m^3)	0.42	16.79	1.33	10.06	4.08	8.39	5.36	6.84	2.76	2.78
27 June 2007	F _T (days)	1.35 (4.36)									
	F _{FW}	0.05	0.18	0.79	0.71	0.98	0.92	0.99	0.99	0.99	1.00
	V _{FW} (10^6 m^3)	5.09	16.84	11.47	10.32	9.13	8.56	6.80	6.84	2.77	2.78
13 June 2008	F _T (days)	3.43 (4.41)									
	F _{FW}	0.24	0.19	0.96	0.72	0.99	0.93	0.99	0.99	0.99	1.00
	V _{FW} (10^6 m^3)	21.75	17.04	13.96	10.37	9.17	8.60	6.82	6.84	2.77	2.78
12 July 2007	F _T (days)	5.30 (4.44)									
	F _{FW}	0.18	0.19	0.97	0.88	0.99	0.99	0.99	1.00	0.99	1.00
	V _{FW} (10^6 m^3)	16.55	17.09	13.98	12.77	9.16	9.22	6.81	6.84	2.77	2.78
10 August 2007	F _T (days)	1.12 (1.11)									
	F _{FW}	0.35	0.19	0.98	0.90	0.99	0.99	0.99	1.00	0.99	1.00
	V _{FW} (10^6 m^3)	31.63	17.11	14.12	12.98	9.16	9.23	6.81	6.84	2.77	2.78
24 August 2007	F _T (days)	1.75 (1.33)									
	F _{FW}	0.13	0.18	0.87	0.81	0.99	0.98	0.99	1.00	0.99	1.00
	V _{FW} (10^6 m^3)	11.99	16.83	12.65	11.72	9.22	9.12	6.84	6.84	2.78	2.78
07 Septemb er 2007	F _T (days)	1.18 (1.28)									
	F _{FW}	0.12	0.19	0.97	0.74	0.99	0.95	0.99	1.00	0.99	1.00
	V _{FW} (10^6 m^3)	10.84	17.06	13.97	10.71	9.20	8.78	6.83	6.84	2.78	2.78
21 Septemb er 2007	F _T (days)	3.67 (3.89)									
	F _{FW}	0.01	0.18	0.66	0.72	0.99	0.93	0.99	1.00	0.99	1.00
	V _{FW} (10^6 m^3)	1.37	16.83	9.52	10.37	9.18	8.61	6.82	6.84	2.77	2.78
21 Septemb er 2007	F _T (days)	2.5 (3.83)									

Table. 3. Flushing time during the post-monsoon

		Segment-1		Segment-2		Segment-3		Segment-4		Segment-5	
Segment Vol. (10^6 m^3)		89.58		14.40		9.23		6.84		2.78	
		Obs	Model	Obs	Model	Obs	Model	Obs	Model	Obs	Model
05 October 2007	F_{FW}	0.09	0.18	0.79	0.67	0.99	0.86	0.99	0.99	0.99	1.00
	V_{FW} (10^6 m^3)	8.30	16.80	11.38	9.71	9.22	7.95	6.84	6.83	2.78	2.78
	F_T (days)	6.65 (7.61)									
19 October 2007	F_{FW}	0.12	0.18	0.60	0.67	0.95	0.85	0.99	0.99	0.99	1.00
	V_{FW} (10^6 m^3)	11.47	16.80	8.64	9.69	8.83	7.93	6.82	6.83	2.77	2.78
	F_T (days)	6.65 (7.60)									
02 November 2007	F_{FW}	0.13	0.18	0.65	0.65	0.97	0.77	0.99	0.96	0.99	0.99
	V_{FW} (10^6 m^3)	11.96	16.80	9.46	9.40	8.99	7.17	6.83	6.61	2.78	2.78
	F_T (days)	19.55(20.89)									
16 November 2007	F_{FW}	0.07	0.18	0.52	0.65	0.91	0.77	0.99	0.96	0.99	0.99
	V_{FW} (10^6 m^3)	6.59	16.80	7.63	9.39	8.43	7.15	6.81	6.60	2.78	2.78
	F_T (days)	15.74(20.87)									
30 November 2007	F_{FW}	0.08	0.18	0.47	0.65	0.85	0.77	0.99	0.96	0.99	0.99
	V_{FW} (10^6 m^3)	7.41	16.79	6.88	9.37	7.85	7.12	6.79	6.60	2.78	2.78
	F_T (days)	15.49(20.84)									
14 December 2007*	F_{FW}	0.16	0.18	0.56	0.64	0.79	0.72	0.89	0.91	0.96	0.98
	V_{FW} (10^6 m^3)	14.95	16.79	8.19	9.29	7.37	6.73	6.15	6.29	2.68	2.75
	F_T (days)	43.81(46.58)									
11 January 2008	F_{FW}	0.03	0.18	0.29	0.64	0.56	0.70	0.82	0.88	0.94	0.97
	V_{FW} (10^6 m^3)	3.25	16.79	4.27	9.25	5.18	6.2	5.67	6.04	2.62	2.70
	F_T (days)	56.54 (111.23)									
25 January 2008	F_{FW}	0.05	0.18	0.28	0.64	0.55	0.70	0.81	0.88	0.93	0.97
	V_{FW} (10^6 m^3)	5.16	16.79	4.09	9.25	5.13	6.53	5.61	6.04	2.61	2.71
	F_T (days)	60.85 (111.30)									

*Flushing time for this month was calculated using surface salinity

Table 4. Flushing time during the pre-monsoon

		Segment-1		Segment-2		Segment-3		Segment-4		Segment-5	
Segment Vol. (10^6 m^3)		89.58		14.40		9.23		6.84		2.78	
		Obs	Model	Obs	Model	Obs	Model	Obs	Model	Obs	Model
08 February 2008	F _{FW}	0.03	0.18	0.28	0.64	0.54	0.69	0.79	0.86	0.93	0.96
	V _{FW} (10^6 m^3)	3.52	16.79	4.14	9.24	5.00	6.45	5.43	5.94	2.60	2.69
	F _T (days)	108.98(216.42)									
22 February 2008	F _{FW}	0.03	0.18	0.23	0.64	0.50	0.69	0.76	0.86	0.93	0.96
	V _{FW} (10^6 m^3)	3.26	16.79	3.39	9.24	4.62	6.46	5.26	5.95	2.58	2.69
	F _T (days)	100.73 (216.49)									
07 March 2008	F _{FW}	0.01	0.18	0.18	0.64	0.41	0.69	0.68	0.85	0.89	0.96
	V _{FW} (10^6 m^3)	1.66	16.79	2.66	9.22	3.81	6.41	4.72	5.88	2.50	2.67
	F _T (days)	148.15(395.43)									
21 March 2008	F _{FW}	0.02	0.18	0.17	0.64	0.39	0.69	0.64	0.85	0.88	0.96
	V _{FW} (10^6 m^3)	2.16	16.79	2.56	9.23	3.61	6.41	4.45	5.88	2.45	2.67
	F _T (days)	147.10(395.47)									
04 April 2008	F _{FW}	0.01	0.18	0.22	0.64	0.49	0.69	0.80	0.85	0.98	0.96
	V _{FW} (10^6 m^3)	1.36	16.79	3.22	9.22	4.56	6.39	5.48	5.86	2.74	2.67
	F _T (days)	251.28(592.38)									
18 April 2008	F _{FW}	0.01	0.18	0.18	0.64	0.42	0.69	0.72	0.85	0.97	0.96
	V _{FW} (10^6 m^3)	1.50	16.79	2.60	9.22	3.92	6.38	4.99	5.86	2.71	2.67
	F _T (days)	227.67(592.32)									
02 May 2008	F _{FW}	0.01	0.18	0.18	0.64	0.42	0.69	0.71	0.85	0.94	0.96
	V _{FW} (10^6 m^3)	1.29	16.79	2.72	9.22	3.94	6.38	4.87	5.86	2.63	2.67
	F _T (days)	199.12(526.49)									
16 May 2008	F _{FW}	0.01	0.18	0.17	0.63	0.38	0.68	0.67	0.85	0.93	0.96
	V _{FW} (10^6 m^3)	1.54	16.79	2.57	9.20	3.56	6.36	4.64	5.85	2.61	2.67
	F _T (days)	192.09 (525.84)									
30 May 2008	F _{FW}	0.01	0.18	0.17	0.63	0.42	0.68	0.72	0.85	0.96	0.96
	V _{FW} (10^6 m^3)	1.06	16.79	2.51	9.21	3.95	6.36	4.93	5.85	2.67	2.67
	F _T (days)	194.89(525.98)									